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DETAILS OF WIND STRUCTURE FROM HIGH RESOLUTION BALLOON SOUNDINGS

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For Aero-Astrodynamics Laboratory

*Prepared by Meteorology Research, Inc.

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George C. Marshall Space Flight Center, Huntsville, Alabama

FOREWORD

This report presents the results of a study conducted by Meteorology Research, Inc., Altadena, California as part of NASA Contract NAS8-5294 with the Aero-Astrophysics Office, Aero-Astrodynamics Laboratory, NASA-George C. Marshall Space Flight Center, Huntsville, Alabama. The NASA contract monitor was Mr. James R. Scoggins; Dr. Robert Stinson was the principal investigator.

The results of this study represent the initial part of a comprehensive analysis of detailed wind profile data. The analysis of small scale features on vertical wind velocity profiles has not been possible heretofore because of measurement limitations. This study makes a substantial contribution toward the understanding of small scale motions at high altitudes. This knowledge should be greatly extended as the contract work continues.

The contract period covered by this portion of the contract was April 1963 to April 1964.

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ABSTRACT

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The tracking of spherical superpressure balloons by an FPS-16 radar has generated accurate data concerning the winds in the upper troposphere and lower stratosphere. Above about 11 km the winds are obtained to high resolution, while below this altitude spurious balloon motions mask the fine structure of the wind although the gross features of the wind are still accurately displayed. At Cape Kennedy 87 soundings are investigated, with most attention being focused on 2 series of 9 and 18 soundings spaced approximately 45 minutes apart.

All the soundings, covering various meteorological situations, show a large amount of microstructure in the wind field above the tropopause, with shears of 2 mps/100 m being observed on all soundings, shears exceeding 5 mps/100 m being observed occasionally, and with the speed (and direction) variations tending to occur with vertical wave lengths of 0.5 to 2 km. The shears occur at an altitude range and are of a magnitude and wave length where they can significantly affect vertically rising rocket launch vehicles.

The sequence soundings show that the large measured individual speed variations tend to persist for a matter of hours, sometimes exceeding 6 hours. Thus the variations are not turbulence but are instead manifestations of an intricate vertical layering of the air at these levels. The persistence is such that a forecast of the major shears, based on a one- to three-hour extrapolation of a sounding, appears moderately reliable.

Three possible physical models of mesoscale circulation to explain the observed shears are selected for special consideration: (1) stacked layers of alternating inertial oscillations, (2) phase shifts with height of standing gravity waves (lee waves) in successive atmospheric layers, and (3) paired longitudinal vortices (helicance). Each model is supported by some segments of the data and contradicted by others. It is concluded that more measurements with FPS-16 radar and other tools are needed before a decision can be reached as to the exact physical cause of the observed shearing phenomena. Author

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The data used in this paper were supplied by Mr. James R. Scoggins, George C. Marshall Space Flight Center, Huntsville, Alabama, and his encouragement and suggestions greatly helped the program. The authors wish to thank Dr. T. B. Smith and Dr. P. B. MacCready, Jr., of MRI who offered many valuable suggestions during the course of this study.

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

TECHNICAL MEMORANDUM X-53115

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SECTION I. INTRODUCTION

The advent of precision missile launchings has generated a requirement for more detailed vertical wind profile data than can be provided by standard GMD wind systems. Machine plottings of records from 87 FPS-16 trackings of special superpressure spherical balloons released from Cape Kennedy, Florida, between 17 November 1961 and 30 April 1963 provide high resolution data for the study of the details of wind structure under differing synoptic conditions. This detail makes these data considerably more valuable than those obtained from standard, less refined, wind measurement systems. This paper investigates the characteristics and possible causes of small scale, apparently organized and persistent (up to several hours), wind variations that are above the noise level of the FPS-16 system.

The observed wind oscillations must be associated with ageostrophic flow, since the observed detailed shears cannot be accounted for quantitatively by the thermal wind equation through the levels in question.

SECTION II. DATA

The wind data used in the present investigation consist of 87 individual soundings taken on 62 separate days, primarily in the winter half of the year. For study purposes the soundings were divided into three groups: (1) serial ascents where a number of soundings were taken in sequence over a relatively short period of time; there are two sets of these; (2) synoptic sequences where soundings were taken at least once a day over a period of two or more days; there are 12 of these sequences; and (3) isolated soundings where there were no other soundings taken on either the day prior or after the particular sounding; there are 23 of these. The value and accuracy of the FPS-16 wind data have been discussed elsewhere (Leviton, 1962, and Scoggins, 1963). Where wind shear values are given in this report, the denominators denote the height intervals over which the measured velocity changes actually occurred.

The temperature data consist of 22 standard radiosonde runs taken at Cape Kennedy as close to the time of the FPS-16 soundings as possible (usually within one or two hours).

SECTION III. SERIAL ASCENTS

The first set of 18 serial ascents was taken between 1100Z on 3 January and 0013Z on 4 January 1963. The sequence began shortly after a short wave trough line at the 500-mb level passed the Cape Kennedy area. A second set of 9 serial ascents was taken between 1227Z and 2032Z on 18 March 1963 at a time when a weak 500-mb ridge dominated the Cape Kennedy region.

Figures 1 and 2 show the FPS-16 wind speed and direction profiles for 3 January and 18 March, respectively. It is quite apparent that there is considerable scatter in the data at low levels. MacCready and Jex (1964) found that at supercritical Reynolds number the balloon follows a random meandering spiral which is not closely related to the wind. At subcritical Reynolds number this is replaced by a fairly regular zigzag or spiral motion with a small amplitude, and so, considering the 4-second radar averaging, the balloon motion accurately shows the wind motion. Similar conclusions can be drawn from work done by Scoggins (1964) and Murrow and Henry (1964). Reid (1964) found that for superpressure balloons of the size used in this study (2-meter diameter) the critical Reynolds number occurred at approximately 42,000 feet (12.8 km). With these facts in mind, the following general details should be noted in Figures 1 and 2.

(1) Neither of these days displays strong winds.

(2) The critical Reynolds number is somewhat below 12 km.

(3) The cyclonic case (3 January) shows more and larger speed oscillations, particularly above the 8 km level, than does the anticyclonic case (18 March).

(4) The amplitude of the directional oscillations are of the same order of magnitude in the two cases but are much thicker in depth in the anticyclonic case.

(5) In the anticyclonic case it is easier to trace individual features (maxima and minima) over periods of several hours than in the cyclonic case. However, even on 3 January these features do appear to have some persistence.

(6) Positive speed shears in excess of 4 mps/100 m occurred more frequently on 3 January than on 18 March. The same holds true for directional shears ≥ 6°/100 m.

Figure 3 shows two paired speed and direction profiles from 3 January. There is good, if not perfect, correlation in phase between the directional and speed oscillations. The slightly out-of-place relationship indicates that the end points of the wind vectors, when plotted on a hodograph, are on an ellipse or on a distorted figure "8". There seems to be a positive phase correlation between speed and direction fluctuations from the lowest point at which the oscillations emerge from the general noise level up to some level which slowly rises with time and which lies above the level of maximum wind; a positive vertical wind speed shear corresponds with a veering of wind while a negative vertical wind speed shear corresponds to a backing. The relationship is reversed as the balloon ascends above the previously mentioned level: an increase (decrease) in wind speed now corresponds to a backing (veering) in wind direction. It must be noted here, however, that such a clear-cut speed and direction correspondence was not as well defined on the 18 March case, and as such, must not be considered as a proven relationship.

The rate-of-rise profiles for these days (not shown) displayed a wide dispersion of data points; however, it was often possible to correlate the mean rate-of-rise features with similar speed and direction oscillations. Large variations of ±1 to ±2 mps even in the mean profile, and often an order of magnitude larger in the actual data points, were observed quite often in these profiles.

Richardson number (Ri) calculations were made for the four speed and direction profiles closest to the four temperature soundings taken during the 3 January serial ascent series. These calculations were made using a vertical increment of 250 m and using the average wind speed for each 250-m layer so that the speed shear may have been considerably underestimated. The use of vector shears would have given still larger shears. In spite of the underestimations, Ri values less than 1 occur quite frequently. If this criterion is truly indicative of turbulence, then turbulence is possible at many layers in the atmosphere including the stratosphere. It was found that peaks as well as minimums in Ri persisted at approximately the same levels during the 12-hour period.

SECTION IV. SYNOPTIC STUDIES

There were 12 periods in the present data sample when soundings were available on successive days. One 5-day sequence of soundings was selected for detailed discussion because it represented most of the basic characteristics observed in all of the synoptic sequences. This set of soundings was taken beginning on 18 March and ending on 22 March 1963. It is particularly useful because it began with the period of serial ascent taken on 18 March discussed above.

At the beginning of the period a weak ridge extended from Wisconsin to Florida and a closed low was located over western Nebraska. A wide belt of anticyclonic jet stream winds was located well to the north of Cape Kennedy. During this period the closed low moved eastward across the Great Lakes with the jet stream progressing southward as the low moved eastward. By the 19th the southern branch of a broad jet current was affecting the Cape area, although the flow was still very weakly anticyclonic. On the 20th the winds were quite strong and the upper air flow had changed to cyclonic. The region of maximum curvature passed the Cape on the 21st and the winds aloft began to shift to a northwesterly direction. By the end of the sequence a major ridge had moved into the Great Plains area and the trough line had moved out into the Atlantic. The flow at Cape Kennedy at this time was primarily out of the northwest and was once again anticyclonic. A surface cold front passed the Cape area around noon on the 20th.

The speed and direction profiles, Figures 4a and 4b, reflect the changes in the synoptic pattern discussed above. At lower levels the winds shifted to southwest before the frontal passage and to the west-northwest during the period following. The directional oscillation had considerably more amplitude above the primary speed maximum than below. On the speed profiles the oscillations were most intense above 16 km. After the jet moved over the area, the major fluctuations in the speed profiles were observed near the level of maximum wind. The correspondence between speed and direction variations discussed in conjunction with the 3 January serial ascents is not at all as clear-cut as in the present case. In most instances a positive speed shear was associated with veering and a negative shear with backing; however, there are several cases where the reverse is true or where the phase relationship alternates from one relationship to the other and back again, both above and below the level of maximum wind. Therefore, no truly reliable statements on this relationship can be made here.

Over all, the synoptic studies support the findings from the serial ascent studies to the extent that they bear out the existence of large oscillations in both speed and direction and large shears. However, a generally valid phase relationship between speed and direction oscillations is open to question.

The region between 18-20 km is of particular interest because it is usually in a very stable region above the Tropical Tropopause. In this region the speed profiles indicate higher frequency speed oscillations than direction oscillations. The ratio of major speed oscillations to direction oscillations is approximately double. The Polar Tropopause is a region of significant wind change. The strongest positive wind shear is frequently found below and the strongest negative shear above this tropopause. Frequently, however, the Polar Tropopause itself is found in a region of local wind minimum. Positive wind shear regions of less than a half km are frequently found in the stratosphere. The present radiosonde equipment does not have fast enough response to pick up lapse rate discontinuities, if they exist, in this region. The largest directional oscillations between 8 and 16 km are also frequently found in the vicinity of the Polar Tropopause. Speed and directional oscillations near the tropopause can usually be related to discontinuities in the lapse rate; however, most of the oscillations at higher levels (between 16 and 20 km) cannot be explained in terms of lapse rate from the available soundings. The data near the Tropical Tropopause are sparse, but the few that do exist suggest a major speed and direction oscillation at this level also.

SECTION V. ISOLATED SOUNDINGS

Although the isolated soundings contribute little additional information concerning the life of these oscillations or their relationship to synoptic changes, they do support the contention that the mesoscale-type oscillations previously discussed are characteristic of all seasons.

Of particular interest is the sounding for 5 July 1962 which is the only sounding representative of the flat temperature and pressure gradients frequently characterizing southerly latitudes in the summer season. The most prominent features of this sounding are the large direction oscillations that occurred with the low wind speed (Figure 5).

SECTION VI. RELATIONSHIP OF SPEED, DIRECTION, RATE OF RISE, AND TEMPERATURE PROFILES

The temperature profiles lack sufficient resolution to determine if neutral layers are associated with part or all of the wind oscillations, but there is some evidence in this direction. There is a strong suggestion that many of the very large oscillations, particularly those near the Polar or Tropical Tropopause, are in essence the result of broad scale horizontal temperature gradients associated with the thermal structure of the atmosphere near the tropopauses. These characteristic details should be persistent in time, and over large areas, and move with the synoptic pattern. In general it can be stated that the more stable the atmosphere the shallower the oscillation in depth for a particular sounding. Abrupt changes in both speed and direction most frequently accompany lapse rate discontinuities.

Rate-of-rise profiles show an interesting relationship with wind speed. When the profile speeds are light, the scatter of the dots is most pronounced in the lower portion of the sounding and smooths out at higher levels where the rate of rise slows down and the balloon effects, as discussed in Section III, are minimized. As the winds get stronger, the scatter shifts upward and becomes nearly equal in the upper and lower portions of the soundings. When the winds become very strong, the scatter in the upper portion of the sounding becomes quite pronounced. This pronounced change in the scatter of the data at higher levels is probably the result of the effects of distance of the balloon from the observational site rather than an atmospheric phenomenon. Discounting the scatter of the data dots, there are discontinuities in the rate-of-rise profiles. Definite maxima and minima are observed. The extreme points generally coincide with extreme points in one or both of the speed and direction profiles, indicating that the oscillations could have a vertical as well as a horizontal component.

SECTION VII. MESOSCALE CIRCULATION MODELS

At least three alternate models of mesoscale flow are suggested by these data or are reported upon by other authors. They all could conceivably explain the basic characteristic oscillations observed in the soundings; however, each seems to have certain deficiencies.

The first would be stacked layers of alternating inertial oscillations characterized by inflow and outflow toward and away from low pressure.

Sawyer (1961) has described quasi-periodic wind variations with height in the lower stratosphere, persisting for periods of hours, based on observations made at Crawley, England. The Crawley oscillations were similar in characteristics to those at Cape Kennedy. He described the disturbances which give rise to these variations as having vertical dimensions of 1 km or so and horizontal dimensions much greater (at least 4 km). He further used perturbation theory to show that slow inertial oscillations might have such dimensions. He concluded that these disturbances in the stratospheric wind flow were the result of a balance between inertial, Coriolis, and static stability effects.

Barbé (1958), using an automatic-following radar, found oscillations similar in amplitude to those described by Sawyer. He found that these wind variations occur over layers 1 or 2 km thick and that their main features, including the altitude of maximum and minimum wind, were repeated on soundings separated in time by periods of 5-10 minutes. Clem (1954), using GMD-I observations, reported similar fluctuations with height, but these fluctuations were considerably greater in amplitude than those found at Crawley. Reiter (1958) suggested that the GMD-I oscillations might be of instrumental origin because their wave lengths coincided with the periods of observation and smoothing. Neiburger and Angell (1956) observed inertial oscillations in the tracks of constant pressure balloons. The rather small vertical movements of these balloons probably allowed them to sample oscillations within a rather narrow belt.

Reed (1964) uses Sawyer's results, rocket trails, and ozone concentrations to support the existence of oscillations in the stratosphere. Danielsen (1959, and again in 1964) stressed the laminated structure of the atmosphere showing that small scale structure in lapse rate persists for considerable periods in both time and space. Reiter, with the present data, found some of the wind oscillations to be associated with lapse rate discontinuities.

This model has considerable appeal in that the wind speed and direction in successive layers would not necessarily have to be in a strict and constant phase relationship. The only requirement would be that the period of the oscillation along an isentropic surface should be close to or larger than one-half a pendulum day. The principal drawbacks to this model are:

(1) No reliable theory has been advanced to explain why the atmosphere would prefer to remain laminated under the influence of mixing and frictional forces.

(2) The data seem to indicate that the periods of the oscillations along isentropic surfaces are considerably less than one-half a pendulum day. This would require some shortening mechanism as described by Sawyer (1961).

(3) This model would not account for the observed oscillations in the rate of rise profiles as it does not contain large scale organized vertical motions.

The second model requires phase differences in standing gravity-type waves (lee waves) contained within stacked layers. Where the crest of the wave in the lower layer is aligned with the trough of the wave in the upper layer, one would expect a wind speed maximum. Where the trough of the lower wave is aligned with the crest of the upper one, a wind speed minimum would be expected. If several of these crest-trough systems were stacked one above the other, as is often observed in lee waves, the measured speed oscillations could be explained.

The principal advantage to this model is that it allows for very persistent wind features (both maximums and minimums) as long as one may assume a steady state of the atmosphere. There would be reason to expect that the balloon would go through the same parts of the system during each ascent. The greatest drawback to the model is concerned with the rather deficient schemes used to describe the conditions favorable or unfavorable for lee wave generation. It is difficult to explain a series of oscillations by a model involving lee waves when we do not even know if a lee wave could exist at the time of the balloon ascents.

The third model consists of stacked layers of oppositely directed or paired longitudinal vortices for which the term "helicance" is suggested.

Kuettner (1959), when discussing banded structure (cloud streets) of cloud systems, described flow similar to what is called helicance here. He described cloud streets as oriented in the general direction of the flow. This banded structure covers a considerable portion of cloud layers and may be found at all latitudes. Kuettner cites the experience of glider pilots who use the term "wind thermal" to express their observations that a combination of thermal convection and strong winds is required to produce cloud streets. He describes typical dimensions for cloud streets to the 50 km in length and 5-10 km in spacing from axis to axis. However, he further states that cloud streets of several hundred km have been observed with characteristic layer depths of 1-1/2 to 3 km where the crosswind spacing of the cloud street lies frequently between two and three times the height of the convection layer. He describes cloud streets as having a lifetime of the order of one hour. They appear to build up and dissipate on both ends, sometimes in a fashion that suggests that the street as a whole drifts slower than the wind. The dissipation is often seen to start through interference with other growing cloud streets. Glider observations show that vigorous updrafts exist under certain sections of the cloud base, while downdrafts essentially occupy the space between the cloud bands. Under otherwise similar conditions the updrafts below cloud streets are generally estimated to be stronger than the flow in columnar thermals.

Conover (1960) described similar cirrus bands tending to be parallel to the jet stream on the warm side and near the entrance. He observed three categories of bands according to the average spacing between bands. The "major bands" were spaced 4.2 km apart and were 148 km long. The following is quoted from the abstract of his paper:

> "The major bands are created between parallel horizontal vortices through which the air flows in a helical motion. The vortices rotate in opposite directions and cloud forms where the combined motion is upward. The resulting clouds indicate conditional instability in all cases, and their form apparently depends on the steepness of the lapse rate and prevailing vertical shear. Maximum lateral components of motion measured across the tops of the vortices range from 0.6 to 6.0 m sec^{-1}. When these components are combined with the forward speeds, a median angle of 4.4 deg from the large-scale wind direction is found across the tops of the vortices."

If two vortices are assumed for each major band interval, the average vortex width would be 2.1 km. It was observed that the ratio of band spacing to depth of the overturned layer was 1.6. That gives an average horizontal-vertical vortex dimension ratio of 0.8.

There have also been other reported observations of similar banded-type clouds and associated vortex-type circulations (Clem, 1955, and Schaefer, 1957).

In a report on a very comprehensive series of laboratory experiments, Avsec (1939) described three principal types of thermoconvective eddies: (a) Benard cells, (b) "eddies in transverse bands," and (c) "eddies in longitudinal bands." Benard cells are well known; the only point added here is that under the right conditions of vertical shear, these cells align themselves into a wormlike chain. The rare "eddies in transverse bands" were aligned perpendicular to the mean flow and evolved from wave crests and troughs. The final type of eddy was similar to that described by the earlier authors in conjunction with banded cirrus clouds. Coexistence of two or more of these eddies and transformation from one type to another was common. Avsec credits Idrac for the thought that the conditions realized in the high atmospheric layers were favorable to the formation of regular eddies like those obtained in the laboratory. Idrac had discovered periodicity of ascending and descending currents in the low atmospheric layer in direct contact with flat ground. Idrac had also observed the planning flight of large birds grouped in parallel bands about 200 or 300 meters apart. Recording apparatus showed that these birds were placing themselves regularly above the rising airflows that were aligned in the general direction of the wind. Idrac supposed that the layer of air sweeping the heated soil became, by reason of the vertical instability, the seat of convective movements in the shape of gigantic rolls. Winds above the ocean were found to have a similar structure but with smaller ascending speeds.

Woodcock (1942) from observation of soaring birds, Pack (1962) from the motion of two tetroons, Smith (1963) from ground dosage of tracers, and Mee (1964) from aircraft observations of temperature and mixing ratio, have found evidence for helicance-type circulations near the earth's surface over smooth ground or water surfaces.

This model has its appeal in that it explains the observed oscillation in rate of rise much more effectively than do the other two. It would explain the oscillations in scalar wind speed with height and their persistence; however, it would be totally unable to allow for the similar persistence in the wind direction oscillations. The only way the latter could be explained is by postulating that these helicances move across the station at precisely the correct speed to allow successive balloons to rise into alternate helicances. This appears highly unlikely.

SECTION VIII. CONCLUSIONS AND RECOMMENDATIONS

The direction and speed oscillations found in the Cape Kennedy special spherical balloon soundings are real. They are conserved in time and space up to periods of several hours. They are best developed at moderate wind speeds and resemble quasi-sinusoidal oscillations superimposed on the basic wind speed and direction profile. The amplitude of the directional oscillations is frequently quite large at high elevations (16-20 km) and seems to increase with increasing stability and decreasing speed. The speed oscillations appear to be most pronounced in the vicinity of tropopauses or in the warm layer between polar and tropical tropopause if they are observed at the same time. In general, both speed and directional oscillations appear to be related to major lapse rate discontinuities.

The fact that the speed and directional oscillations seem correlated with maxima and minima in the rate-of-rise profiles may be an indication that the oscillations have vertical components.

Localized regions of strong wind shear may occur under all types of flow; however, the strongest speed shears in individual cases typically occur in or near stable layers.

Three mesoscale circulation models have been suggested, and some of their strong and weak points discussed. The models are

(a) Quasi-horizontal stacked layers of alternating inertial oscillations,

(b) Phase differences in stationary gravity-type waves (lee waves) contained within stacked layers,

(c) Paired longitudinal vortices (helicance).

The present data do not allow a decisive choice as to which, if any, of the above models is the correct one to explain the observed oscillations. The benefits to be derived from a physical understanding of the oscillations, however, make it imperative to design future studies toward this goal. One way to approach the problem is to design studies to eliminate one or more of the models.

Critical tests of the lee wave model could be accomplished by plotting the location in space of the persistent wind maximums and minimums. Various balloon launch points would be required (or at least varying balloon ascent speeds so as to vary the drift).

Tests which would probe features of the helicance model could involve the simultaneous release of balloons spaced 5 - 30 km apart, normal to the mean wind direction. Such a setup would give some insight into the horizontal, as well as vertical, structure of the oscillations. The principal feature of the helicance model is its cellular nature; if this feature could not be found in the data, one would conclude that helicance is not the primary physical control.

A test for the stacked quasi-inertial oscillations model would require a setup of FPS-16 soundings similar to that proposed to test the helicance model, plus detailed temperature measurements. The principal feature of the inertial oscillation model is the existence of large, quasi-horizontal layers in the atmosphere, each containing air whose motion has a period of the order of one-half a pendulum day. If these layers were not evident, or if along a given layer the period of oscillation were significantly less than one-half a pendulum day, one would have to dismiss the model or make some indeterminant modifications as done by Sawyer (1961).

All of the above studies are negative in nature in that they try to uncover the physical mechanism behind the observed shears simply by eliminating rather than confirming one or more of the models. It would be advantageous to carry them out, however, as they employ proven measurement methods and consequently might provide valuable information at a small cost.

A more positive series of tests could be performed by releasing smoke or aircraft contrails and photographing their positions in time and space. With such data one could actually see paired vortices or lee waves, if they existed.

SECTION IX. APPLICATION OF RESULTS TO MISSILE OPERATIONS

The wind oscillations studies in this report seem to be of a frequency which might critically affect vertically rising vehicles. It therefore appears important to anticipate for major launch operations the magnitude and spectral characteristics of such oscillations, at least within a range of wave lengths which might trigger response frequencies in the rising missile. This would call for highly sophisticated forecasting procedures which, without knowledge of the physical nature of these oscillations, would have to be based entirely on statistical findings. To lend a certain amount of reliability to such statistics a large backlog of data would be required, covering a sufficient number of cases in each of a large variety of synoptic weather situations and over various launch sites.

In addition to this feasible, and certainly promising, statistical approach, it appears that a knowledge of the physical nature of these wind oscillations would be of considerable help in forecasting the magnitude of the fluctuations whose characteristics seem to affect launch operations.

Even though some of the observed oscillations seem to persist for several hours, we do not know yet what causes their appearance or disappearance in any specific series of soundings, nor what maintains them while they are observed. Therefore, based upon the present data only short-term forecasts, not to exceed one to three hours, could be issued, since from a simple sounding alone there is no indication available as yet what possible development the measured fluctuations might undergo.

Further measurement programs should be designed to furnish both (1) additional data under varying synoptic and terrain conditions in order to expand statistical evidence, and (2) proof or disproof of any of the physical models described above or of any other concepts that may evolve. The suggested multi-balloon survey, augmented by simultaneous aircraft measurements and smoke trail photography might yield the desired information.

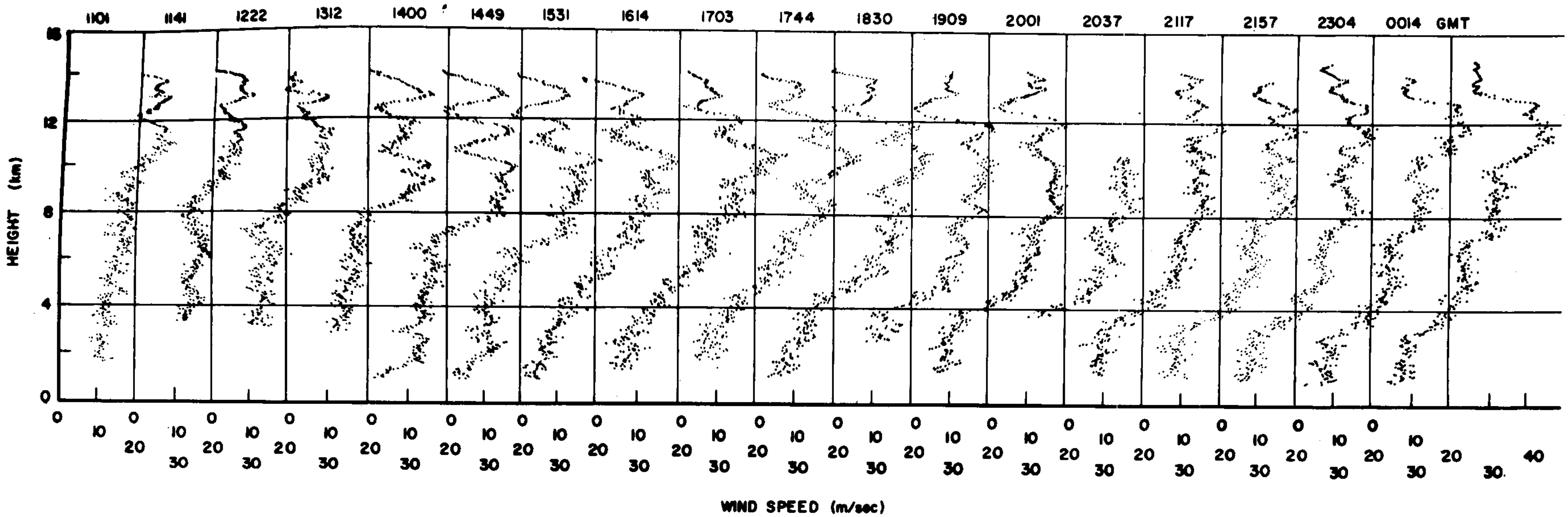

FIGURE 1a. WIND SPEED PROFILE, JANUARY 3, 1963

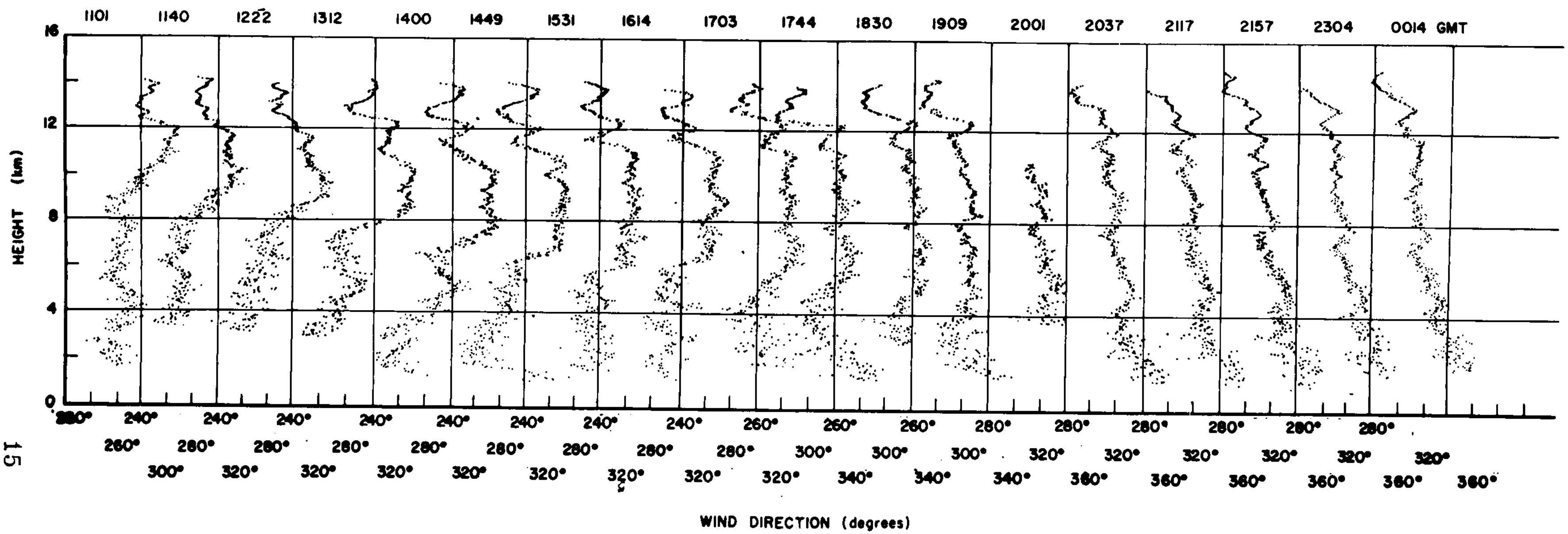

FIGURE 1b. WIND DIRECTION PROFILES, JANUARY 3, 1963

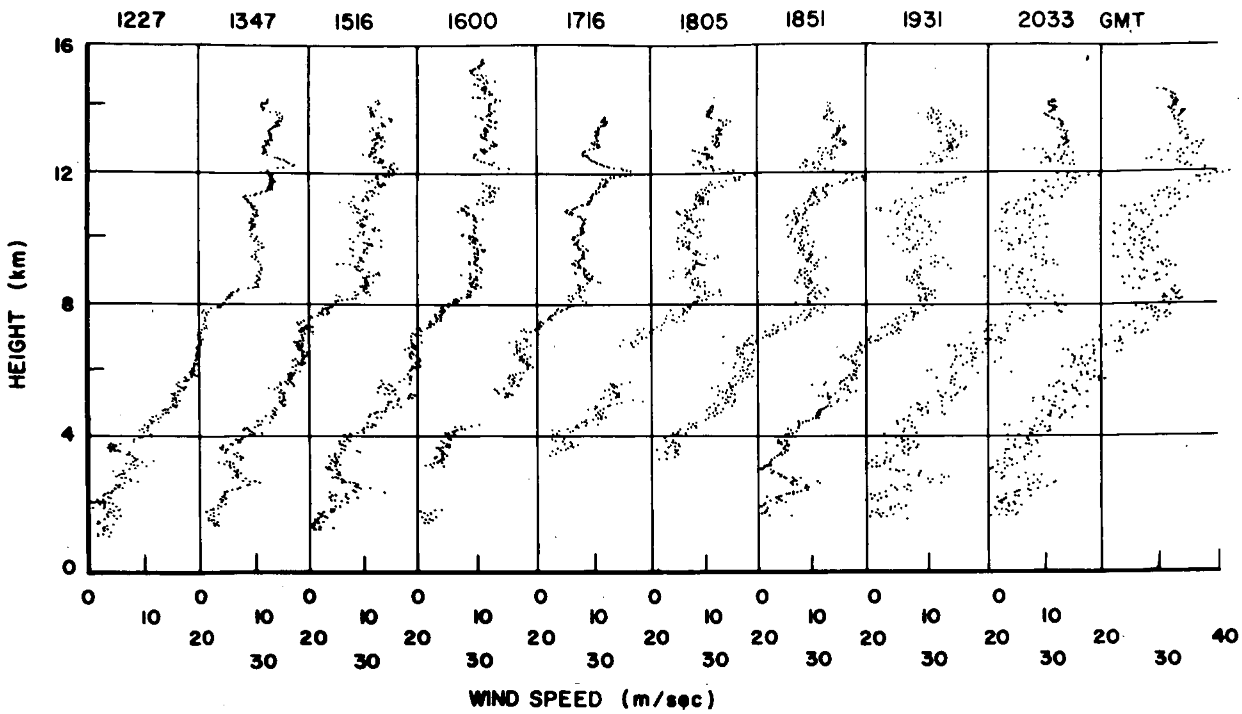

FIGURE 2a. WIND SPEED PROFILES, MARCH 18-22, 1963

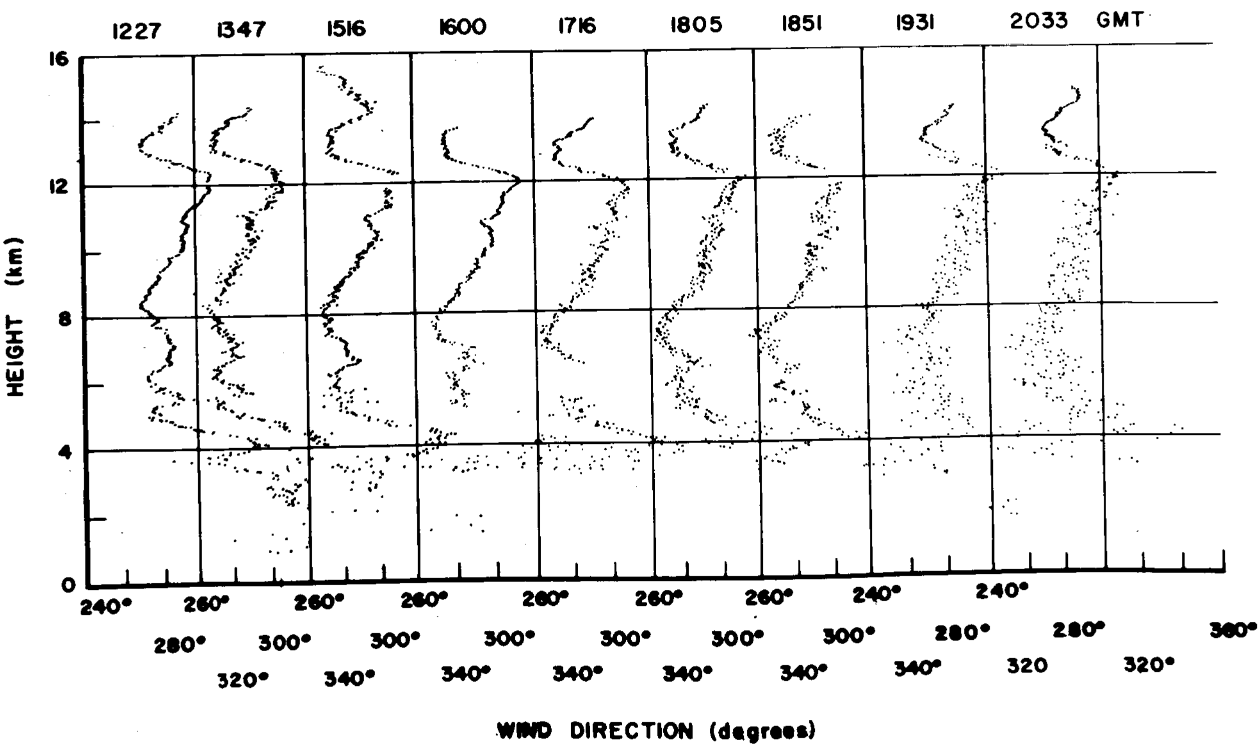

FIGURE 2b. WIND DIRECTION PROFILE, MARCH 18, 1963

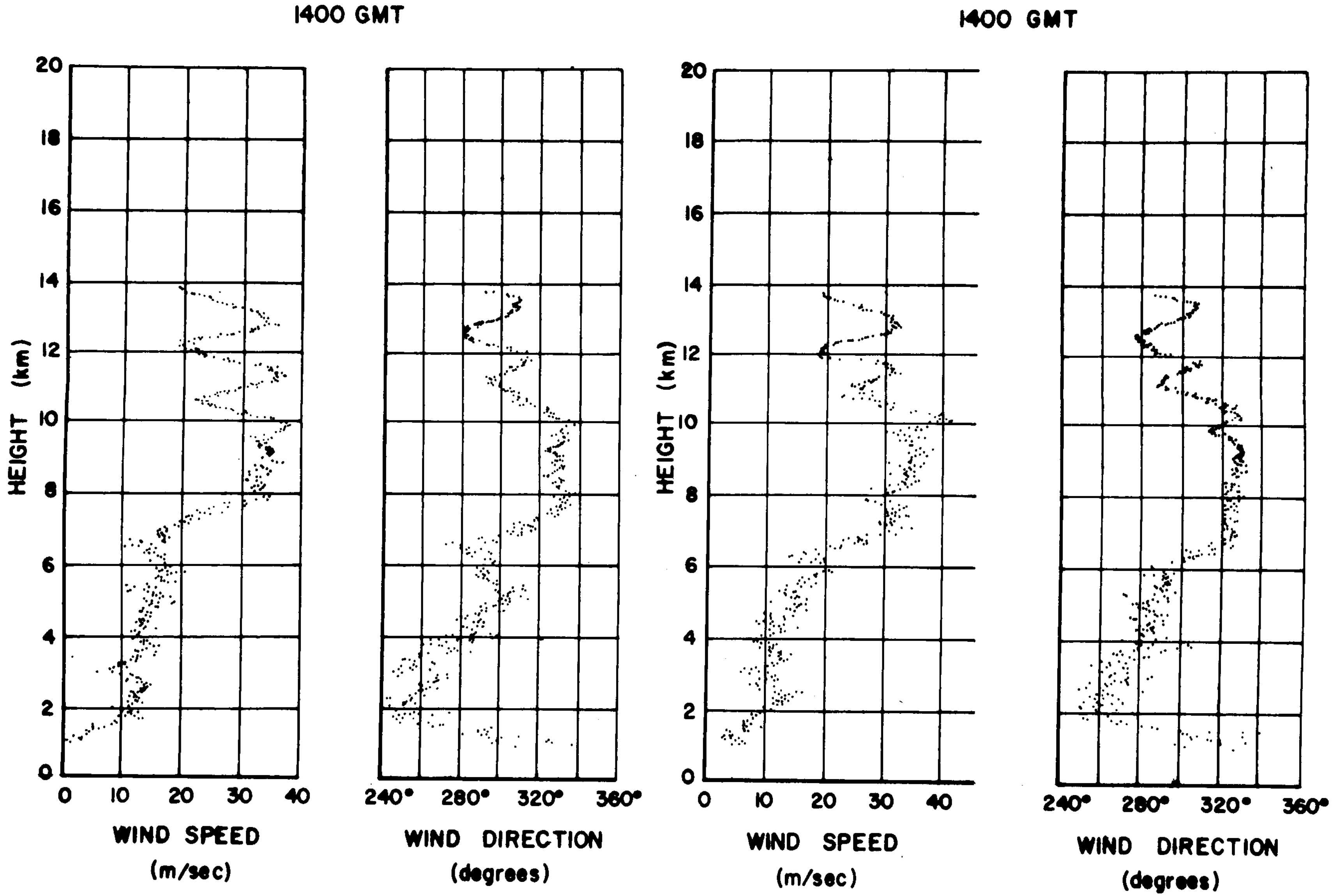

FIGURE 3. PARIED WIND SPEED AND DIRECTION PROFILE, JANUARY 3, 1963, 1400 AND 1449 GMT

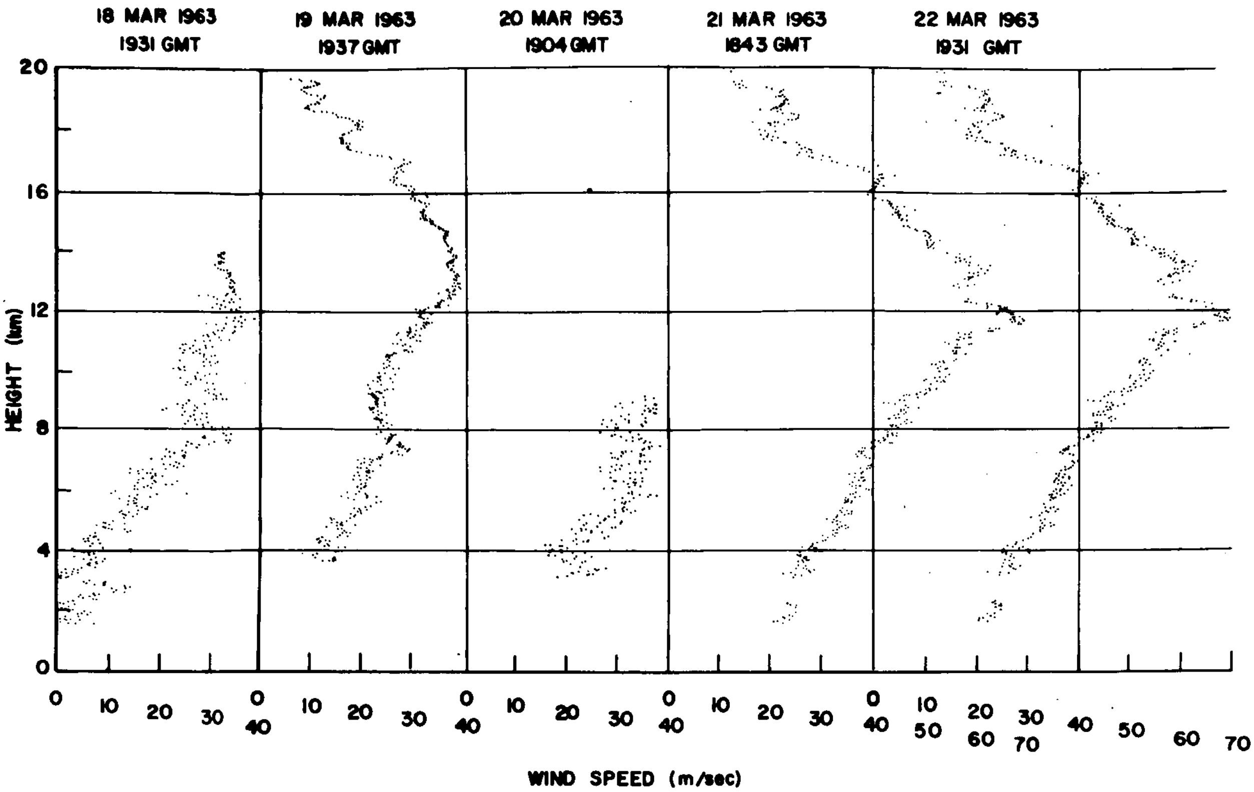

FIGURE 4a. WIND SPEED PROFILES, MARCH 18-22, 1963

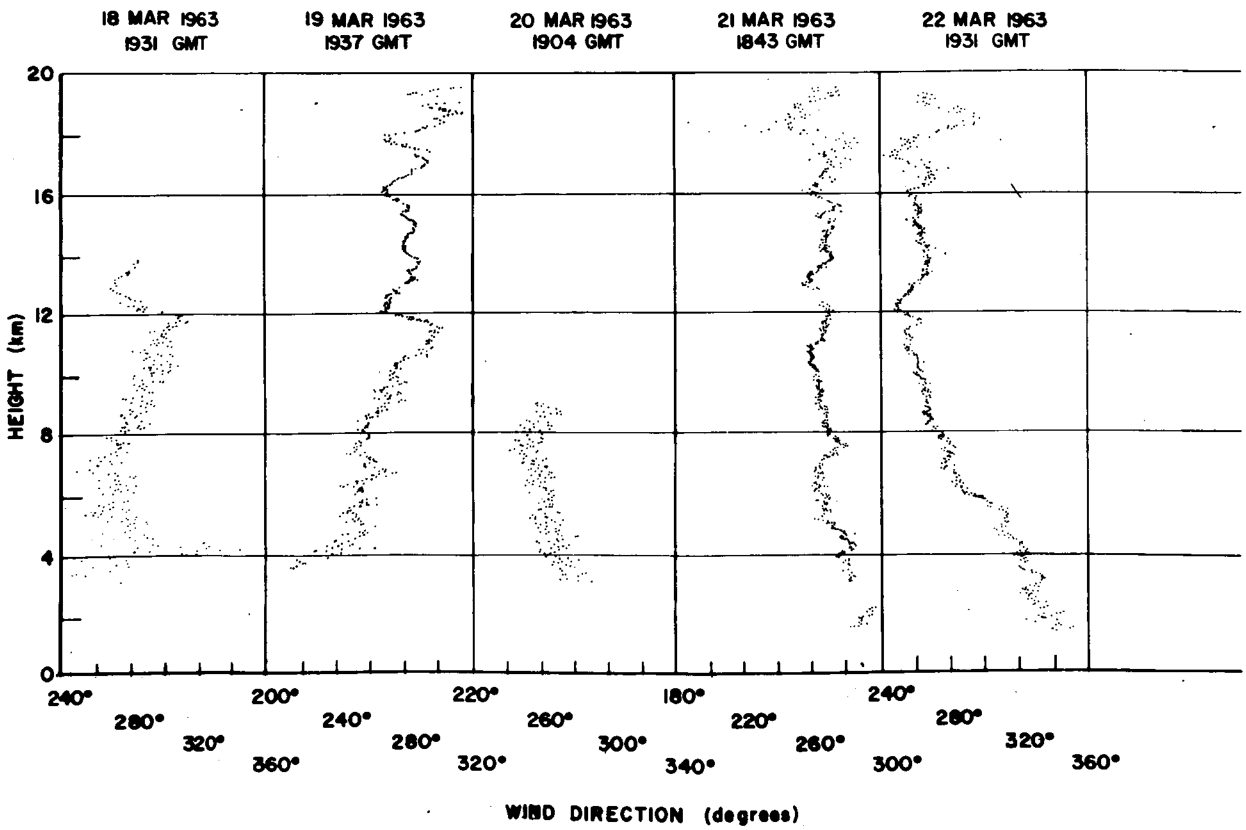

FIGURE 4b. WIND DIRECTION PROFILE, MARCH 18-22, 1963

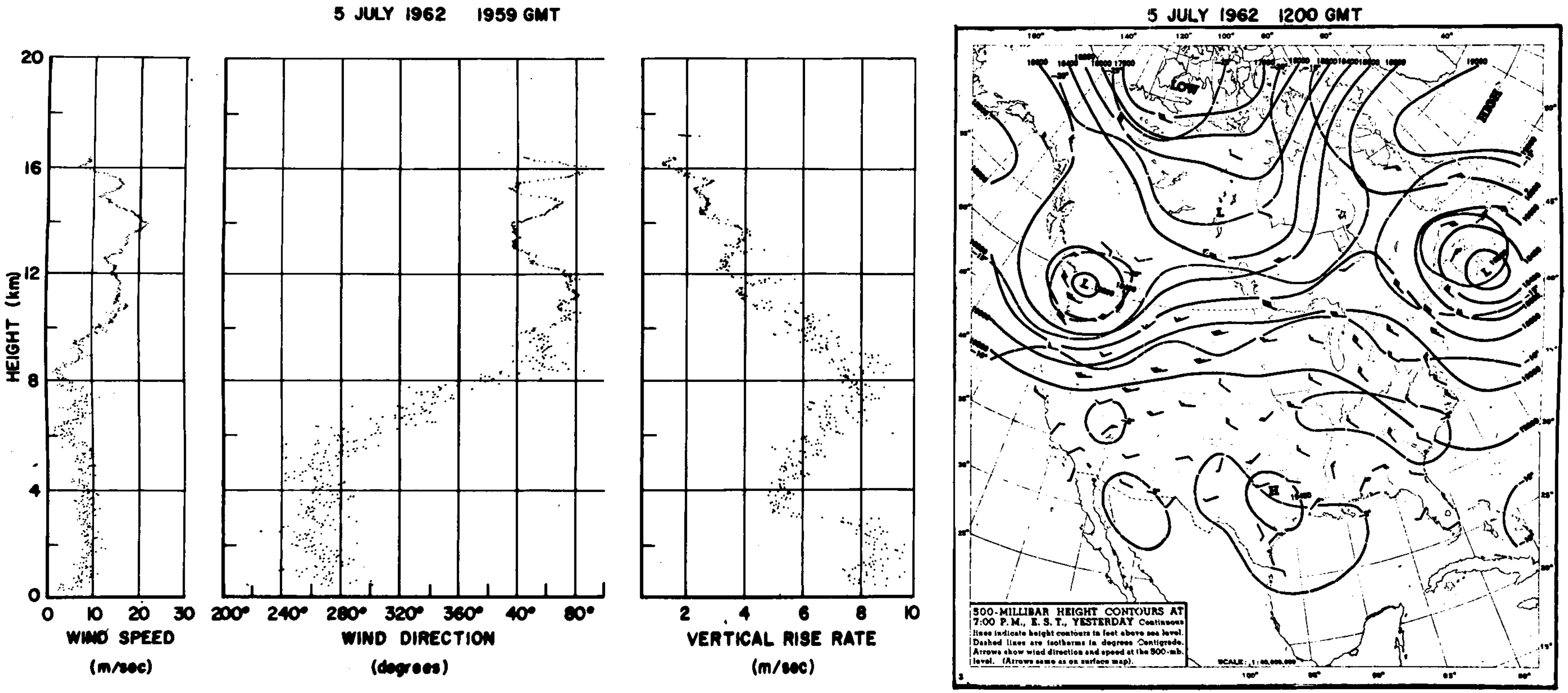

FIGURE 5. FPS-16 SOUNDING AND 500-MB FOR JULY 5, 1962

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DETAILS OF WIND STRUCTURE FROM HIGH RESOLUTION BALLOON SOUNDINGS

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This document has also been reviewed and approved for technical accuracy.

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